

Resummations for Diboson production

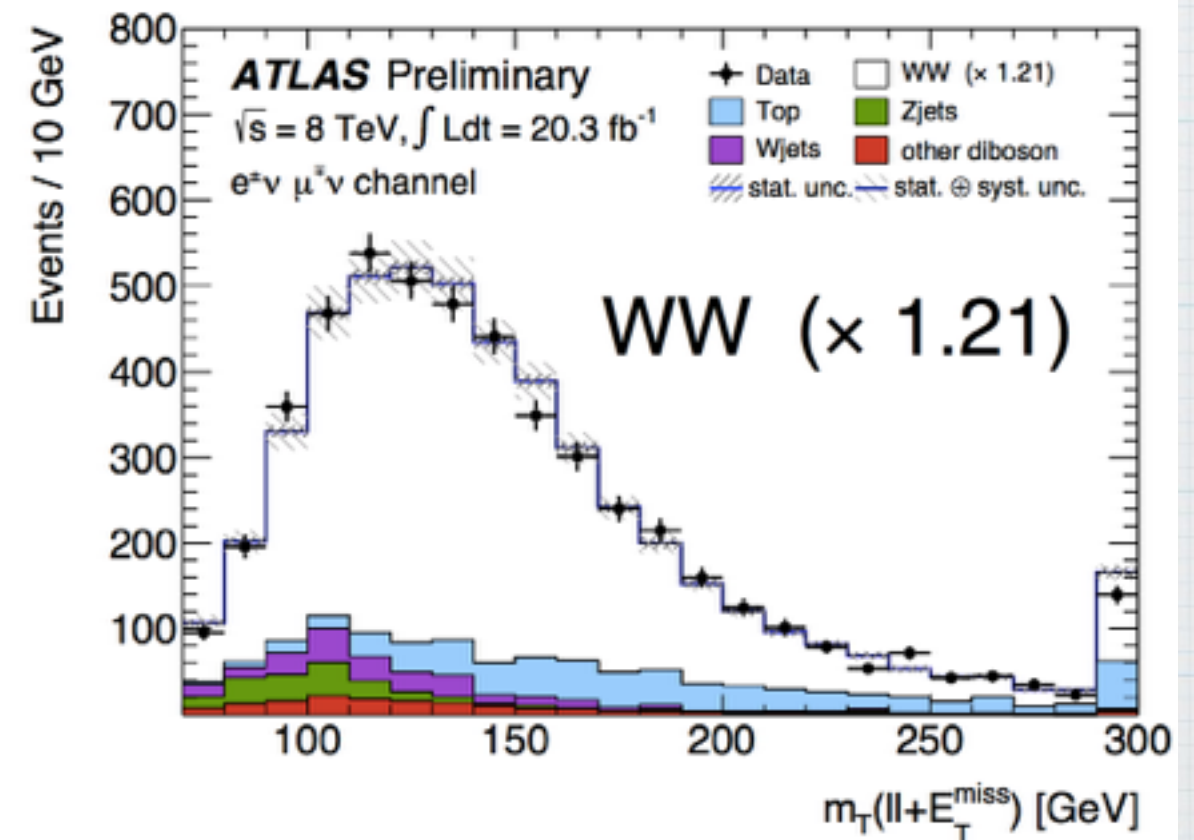
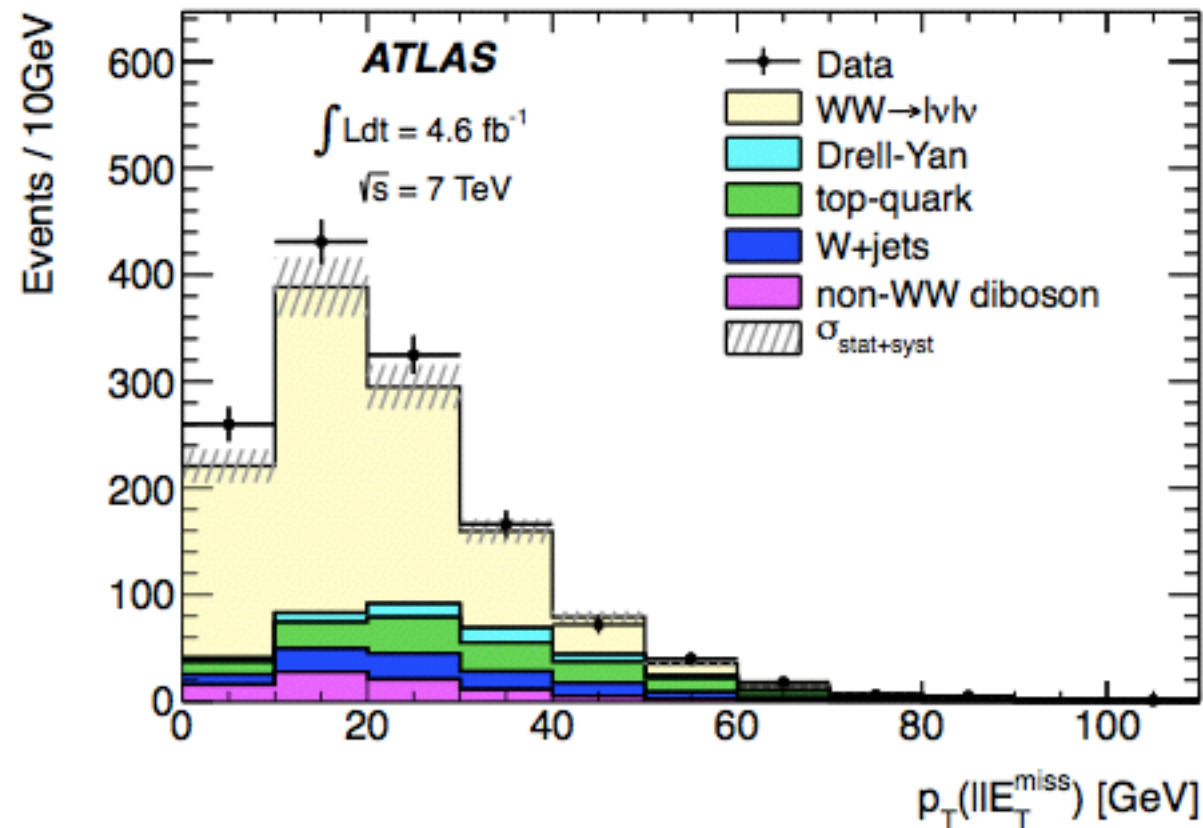
Prerit Jaiswal
Syracuse University

Multi-Boson Interaction Workshop (BNL)

29th October, 2014

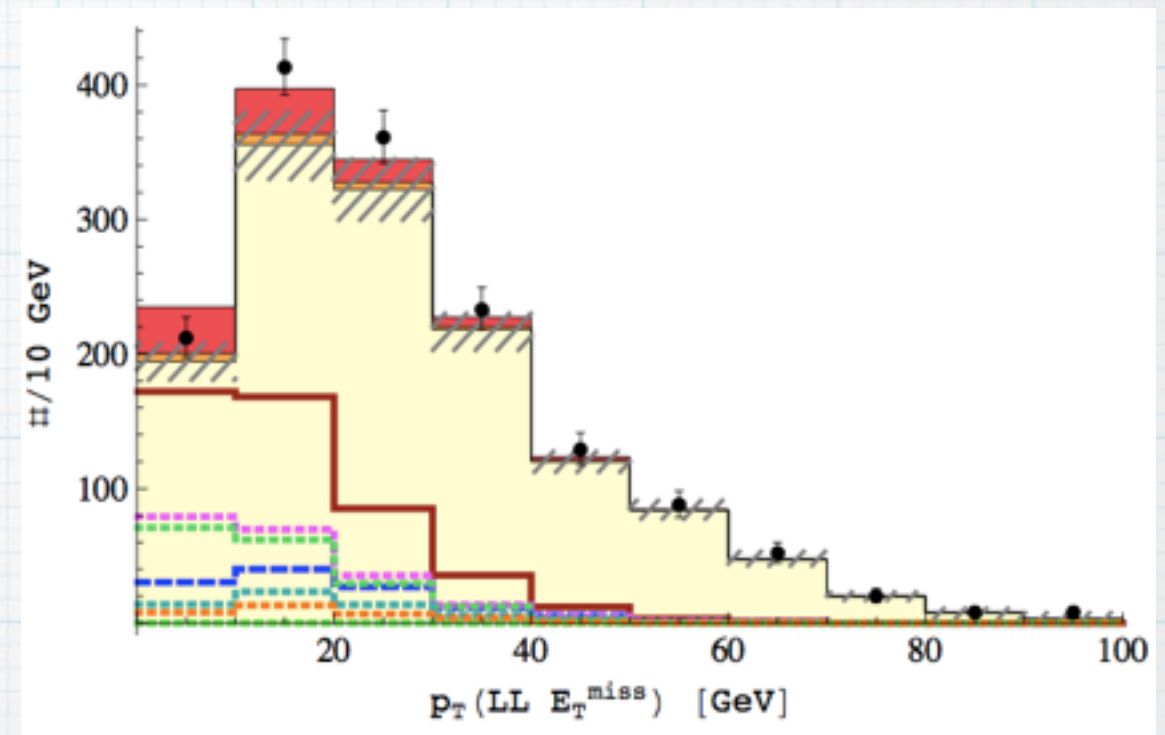
'The WW anomaly'

\sqrt{s}	ATLAS σ [pb]	CMS σ [pb]	Theory (MCFM) σ [pb]
7 TeV	$51.9^{+2.0+3.9+2.0}_{-2.0-3.9-2.0}$	$52.4^{+2.0+4.5+1.2}_{-2.0-4.5-1.2}$	$47.04^{+2.02+0.90}_{-1.51-0.66}$
8 TeV	$71.4^{+1.2+5.0+2.2}_{-1.2-4.4-2.1}$	$69.9^{+2.8+5.6+3.1}_{-2.8-5.6-3.1}$	$57.25^{+2.35+1.09}_{-1.60-0.80}$



New Physics Hiding in Plain Sight?

- * B. Feigl, H. Rzehak, and D. Zeppenfeld, New physics backgrounds to the $H \rightarrow W W$ search at the LHC?, [arXiv:1205.3468].
- * D. Curtin, P. Jaiswal, and P. Meade, Charginos hiding in plain sight, [arXiv:1206.6888].
- * P. Jaiswal, K. Kopp, and T. Okui, Higgs production amidst the LHC detector, [arXiv:1203.1181].
- * K. Rolbiecki and K. Sakurai, Light stops emerging in WW cross section measurements?, [arXiv:1203.5696].
- * D. Curtin, P. Jaiswal, P. Meade, and P.-J. Tien, Casting light on BSM physics with SM standard candles, [arXiv:1204.7011].
- * D. Curtin, P. Meade, and P.-J. Tien, Natural SUSY in Plain Sight, [arXiv:1206.0848].
- * J.S. Kim, K. Rolbiecki, K. Sakurai and J. Tattersall, Stop that ambulance! New physics at the LHC?, [arXiv:1206.0858].



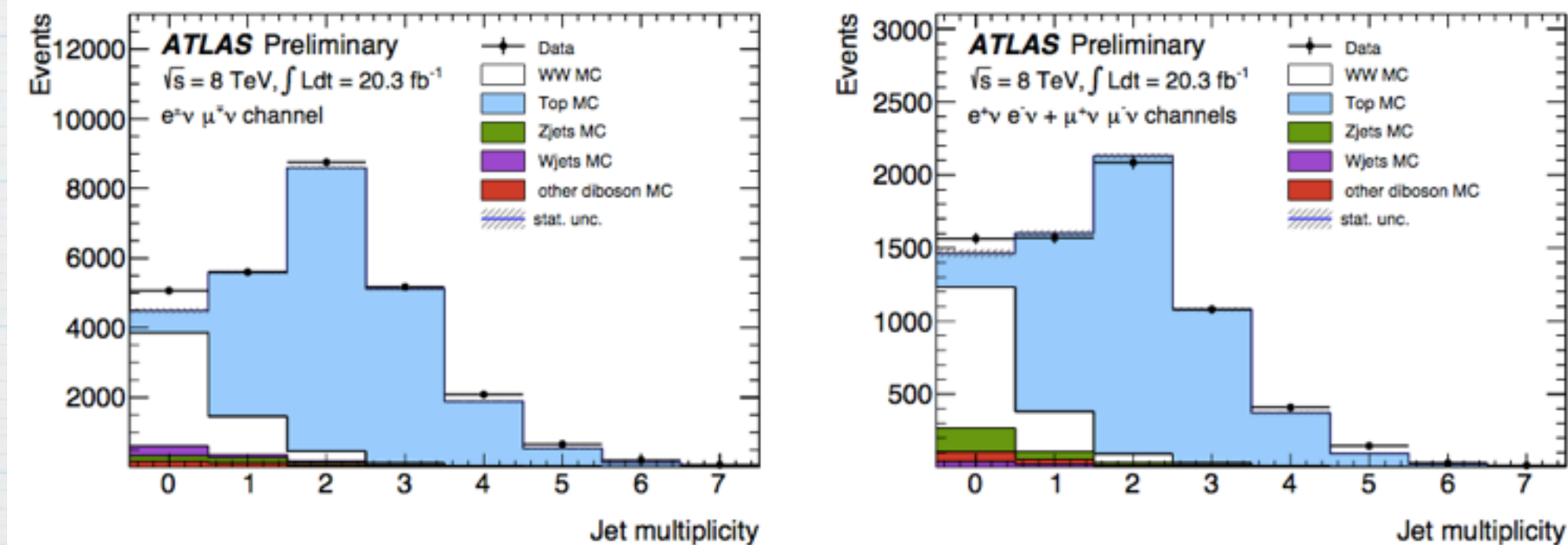
An explanation of the
 WW excess with 110 GeV
charginos

Or simply a QCD effect?

ATLAS-CONF-2014-033 (8 TeV WW measurement)

The jet multiplicity distributions and the different background contributions after applying these requirements are shown in Figure 3 for $e\mu$ and the sum of $ee + \mu\mu$ events. A large contribution from top ($t\bar{t}$ and single top) events is visible for jet multiplicities larger than zero. Hence, to reject these backgrounds, the number of selected jets is required to be zero (jet-veto requirement). There are some discrepancies between the data and the MC prediction visible for the zero jet bin.

Both ATLAS and CMS experiments impose jet-veto in their analysis



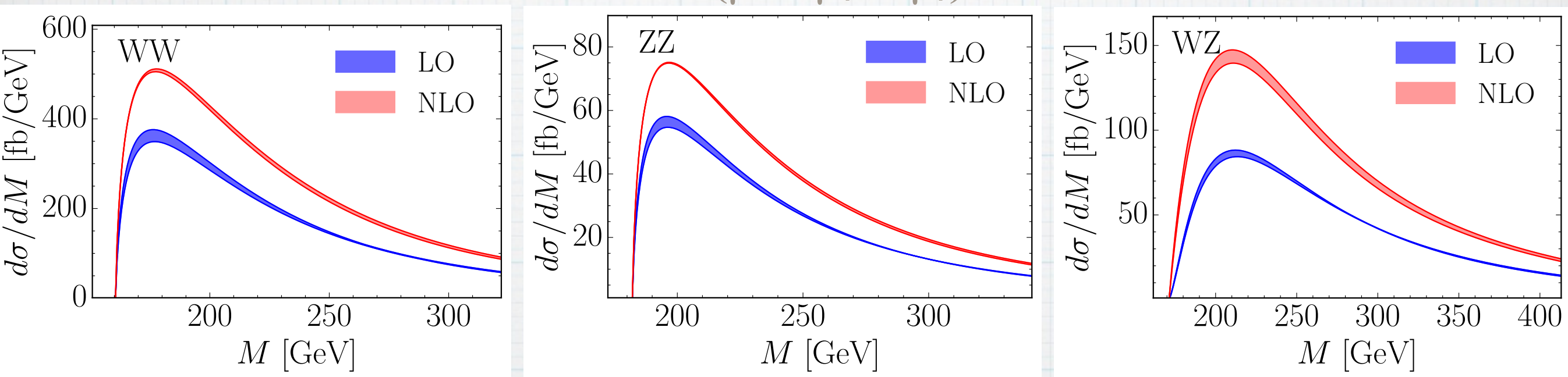
Need a better understanding of jet-veto.

P. Jaiswal and T. Okui, An Explanation of the WW Excess at the LHC by Jet-Veto Resummation, [arXiv:1407.4537](https://arxiv.org/abs/1407.4537).

Or several QCD effects ?

- * WW @NNLO : 5-6 % enhancement w.r.t NLO+gg at 7/8 TeV LHC.
[arXiv:1408.5243]
- * Similar enhancement from 'NLO+ π^2 resummation'.
- * What are the scale uncertainties and do we trust them?

$$M/2 < (\mu = \mu_f = \mu_r) < 2 M$$



- * NLO predictions as much as 30σ away from LO central value.
- * Very poor perturbative convergence? Or underestimated scale uncertainties?

Need a better understanding of scale uncertainties.

P. Jaiswal, A New Perspective on Scale Uncertainties for Diboson Processes, [arXiv:1410.xxxx].

Outline

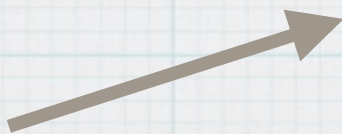
- * Part I : Jet-Veto and Large Logs
- * Part II : Resummation in Effective Field Theories
- * Part III : Complex Scales, Large Logs and Scale Uncertainties
- * Part IV : Results for $WW+0$ jet production at the LHC

Part - I

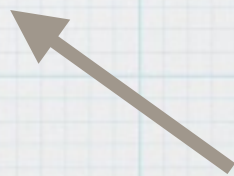
Jet-Veto and Large Logs

Jet-Veto : Origin of Large Logs

- * Jet-veto example : no 'jets' with $p_T > 25 \text{ GeV}$ allowed
- * Jet-veto \implies Many scales \implies Large Logs
- * Inclusive WW measurement :
Only one scale appears : M_{WW}
 \rightarrow Obvious scale choice : $\mu \approx M_{WW}$. [$\mu = \mu_f = \mu_r$]
- * WW + 0 jet measurement :
Two scales appear : M_{WW} and p_T^{veto}
 \rightarrow 2 possible choices : $\mu \approx M_{WW}$ or $\mu \approx p_T^{\text{veto}}$??



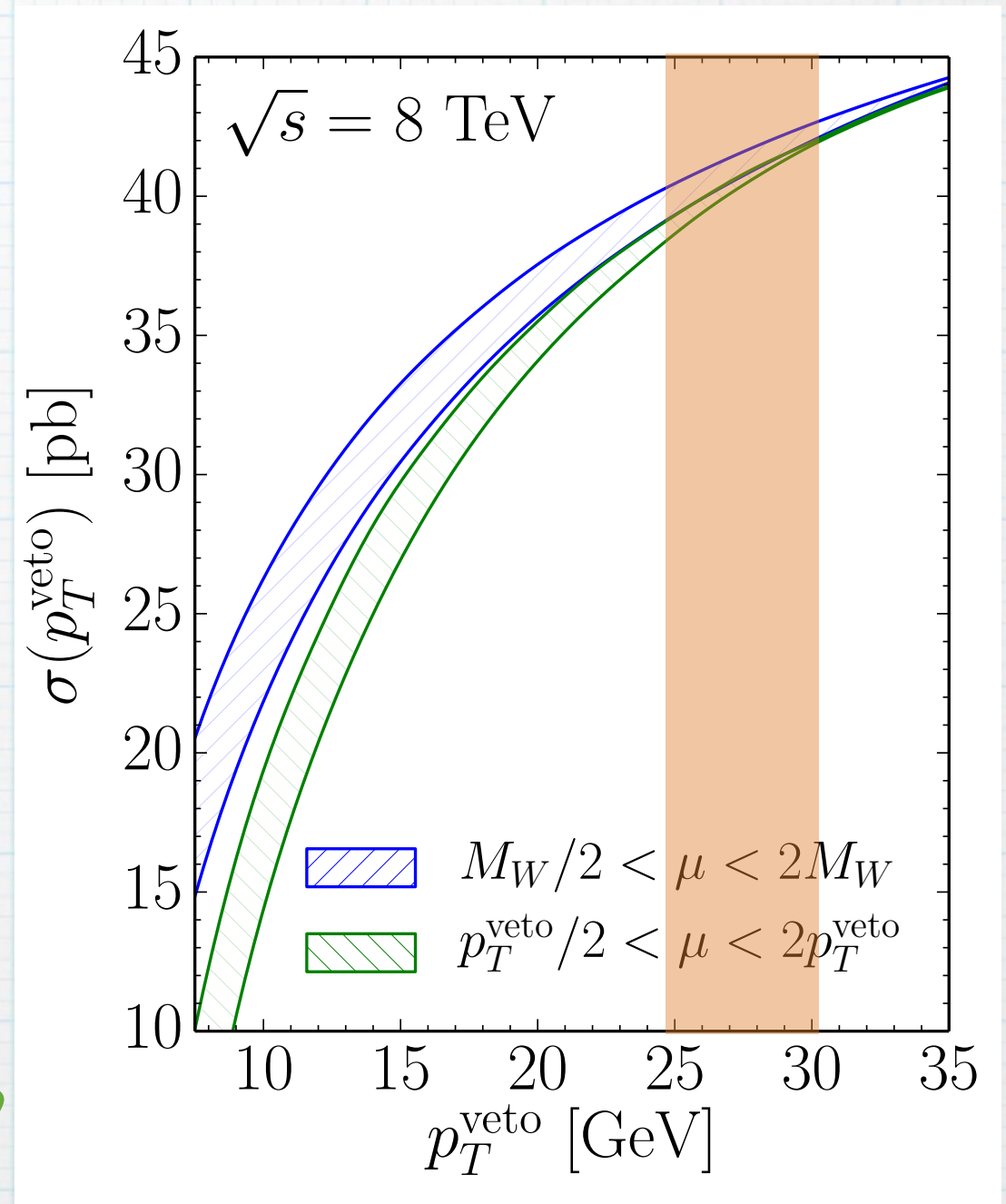
Minimize logs from
virtual diagrams.



Minimize logs from
real diagrams.

Fixed Order Calculations ($pp \rightarrow WW$)

- * Inclusive NLO K-factor ≈ 1.6
- * 0-jet bin, K-factor ≈ 1.1
- * Disagreement at low p_T^{veto} for different scale choices.
- * Agreement for $p_T^{\text{veto}} \approx 25\text{-}30\text{ GeV}$ and reduced scale uncertainty!!
- * Good perturbative convergence ?
....or large log artifacts?



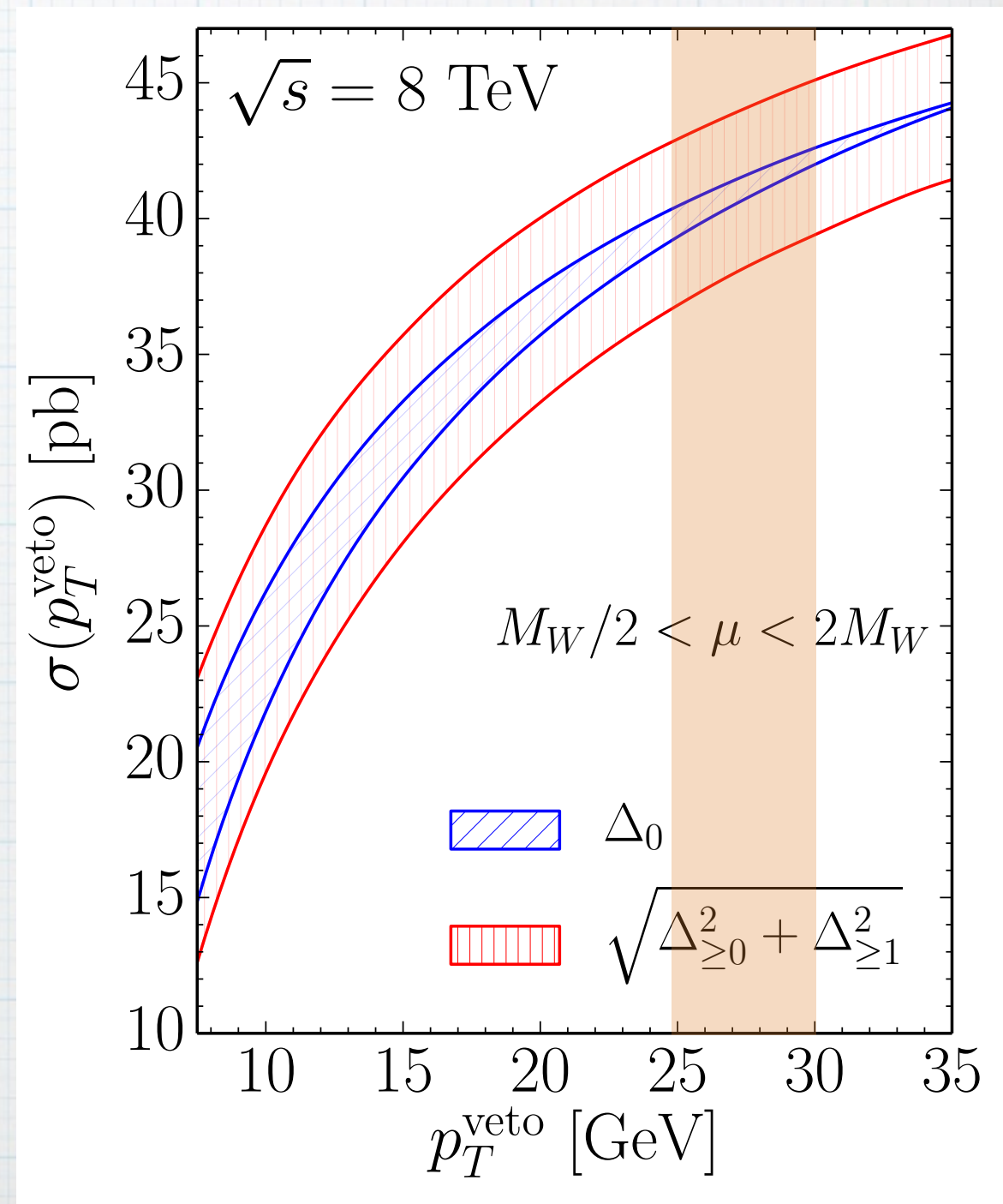
Fixed Order Calculations ($pp \rightarrow WW$)

- * $\sigma_{\geq 0} \approx \sigma_B [1 + \alpha_s + \alpha_s^2 + \dots]$ (Large K-factor)
- * $\sigma_{\geq 1} \approx \sigma_B [\alpha_s (L^2 + L + 1) + \alpha_s^2 (L^4 + L^3 + L^2 + L + 1) + \dots]$ (Large logs)
- * $\sigma_0 = \sigma_{\geq 0} - \sigma_{\geq 1}$ (Large cancellations)

How to deal with accidental cancellations?

. I. W. Stewart and F. J. Tackmann, [arXiv:1107.21171](#).

- * Treat scale uncertainties in $\sigma_{\geq 0}$ and $\sigma_{\geq 1}$ as uncorrelated.
- * Large scale uncertainties in 0-jet bin become evident.



Jet-Veto and Large Logs: The problem of many scales

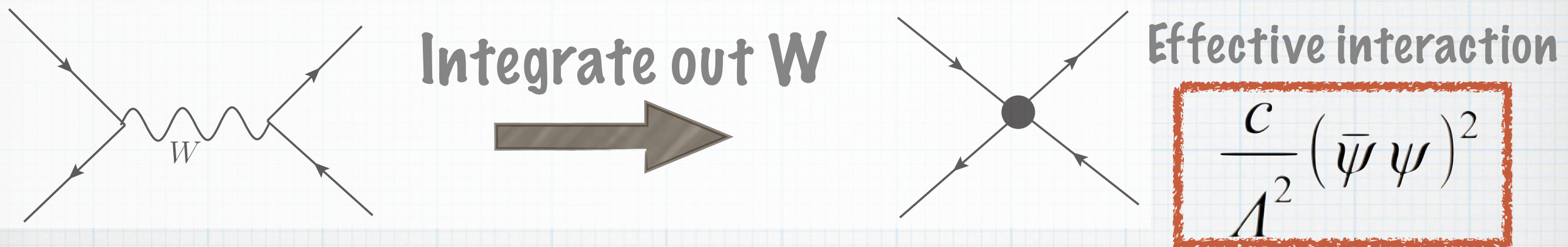


- * A well known and understood problem in EFTs (Effective Field Theories)
- * EFTs can provide answers on how to resum the large logs.

Part - II

Resummation in Effective Field Theories

Example : Fermi's 4-fermion interaction



* Two scales in the problem :

* Λ : scale below which EFT is valid.

$$\frac{1}{\Lambda^2} \sim \frac{g^2}{m_W^2}$$

* m_f : scale at which precision measurements are made

* Origin of large logs :

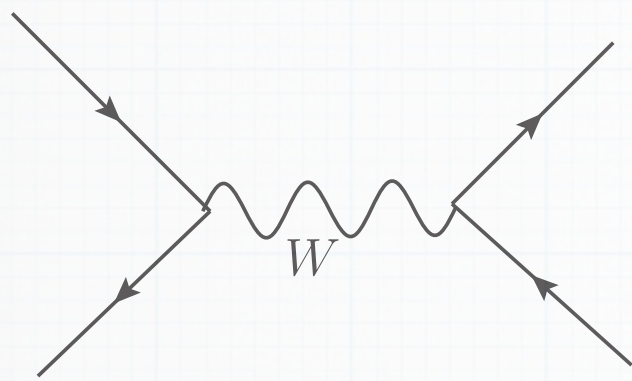
* Tree level : $c^{(0)} \approx 1$

One-loop : $c^{(1)} \approx \frac{\alpha}{4\pi} \log\left(\frac{\mu^2}{\Lambda^2}\right)$

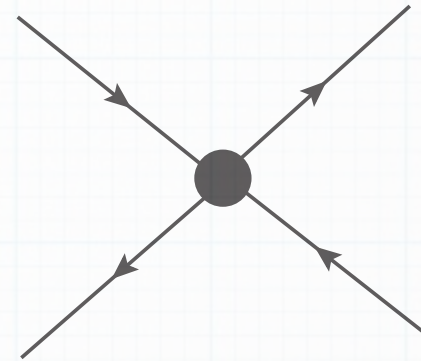
* Large logs for $\mu \approx m_f$ (the measurement scale).

* How does EFT resum the large logs?

Example : Fermi's 4-fermion interaction



Integrate out W



Effective interaction

$$\frac{c}{\Lambda^2} (\bar{\psi} \psi)^2$$

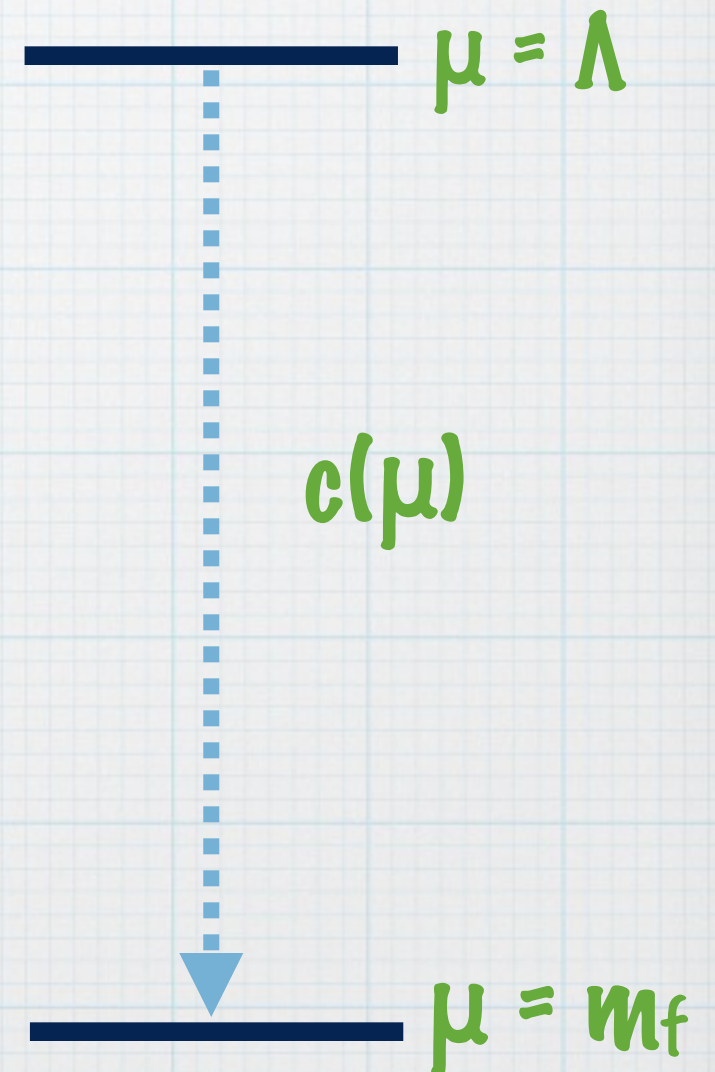
$$c^{(0)} \approx 1$$

$$c^{(1)} \approx \frac{\alpha}{4\pi} \log\left(\frac{\mu^2}{\Lambda^2}\right)$$

Resummation of logs in EFT

- * accomplished through RG running of the coefficient $c(\mu)$ to the desired scale ($\mu = m_f$).

- * Initial condition for $c(\mu)$: Determine $c(\mu = \Lambda)$ by matching to the full theory. No large logs in this step because $\mu = \Lambda$.



Effective Field Theories for the LHC

to describe QCD interactions

Example : Inclusive Hadronic Cross-sections

- * Two scales in the problem :
 - * Hard scale, μ_h : associated with the hard interaction, for example invariant mass of W -pair for WW production.
 - * Soft scale, μ_s : scale of the hadronic masses/ jet masses / Λ_{QCD} / the scale at which PDFs are measured.

$$\sigma = \hat{\sigma}(\mu_h, \mu) \otimes f(\mu_s, \mu) \otimes f(\mu_s, \mu)$$

Partonic
cross-section

PDFs

Effective Field Theories for the LHC

to describe QCD interactions

Example : Inclusive Hadronic Cross-sections

$$\sigma = \underbrace{\hat{\sigma}(\mu_h, \mu)}_{\frac{\alpha_s}{4\pi} \log\left(\frac{\mu_h^2}{\mu^2}\right)} \otimes \underbrace{f(\mu_s, \mu) \otimes f(\mu_s, \mu)}_{\frac{\alpha_s}{4\pi} \log\left(\frac{\mu^2}{\mu_s^2}\right)}$$

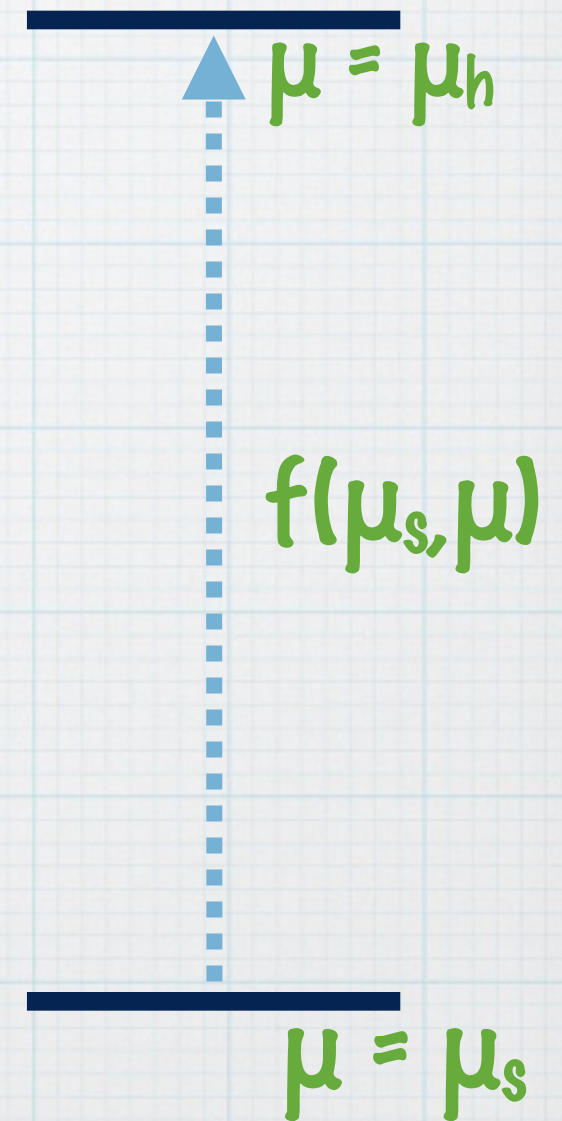
Logs :

No large logs at $\mu = \mu_h$

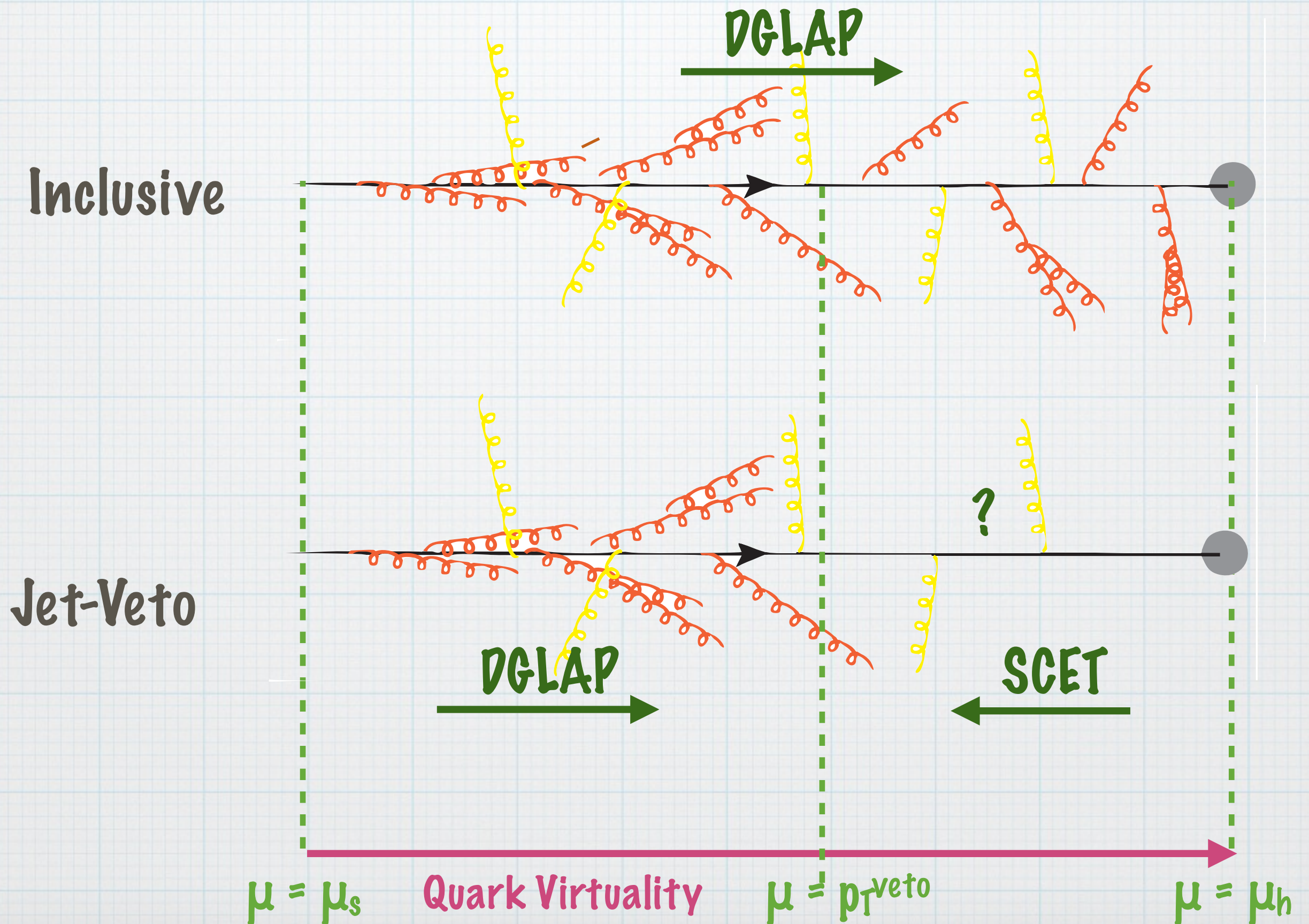
Simply evaluate
partonic cross-section
at $\mu = \mu_h$

large logs at $\mu = \mu_h$

RG evolve PDFs from
 $\mu = \mu_s$ up to $\mu = \mu_h$.
(DGLAP evolution)



Towards EFT for Jet-Veto Cross-sections



Soft Collinear Effective Theory

Describes quark 'jet' with $p_T \sim p_T^{\text{veto}}$

Upshot: RG evolve everything to a common scale ($\mu = p_T^{\text{veto}}$)

$$\sigma = \underbrace{\left| \hat{C}(\mu_h, \mu) \right|^2}_{\text{Wilson Coefficients}} \otimes \underbrace{B_1(\mu_s, \mu) \otimes B_2(\mu_s, \mu)}_{\text{Beam functions}} \otimes \underbrace{A_c(p_T^{\text{veto}}, \mu)}_{\text{collinear anomaly}}$$

Wilson
Coefficients

Logs: $\frac{\alpha_s}{4\pi} \log\left(\frac{\mu_h^2}{\mu^2}\right)$

evolve from
 μ_h to p_T^{veto}

$$\hat{C} = U \times C$$

Beam
functions

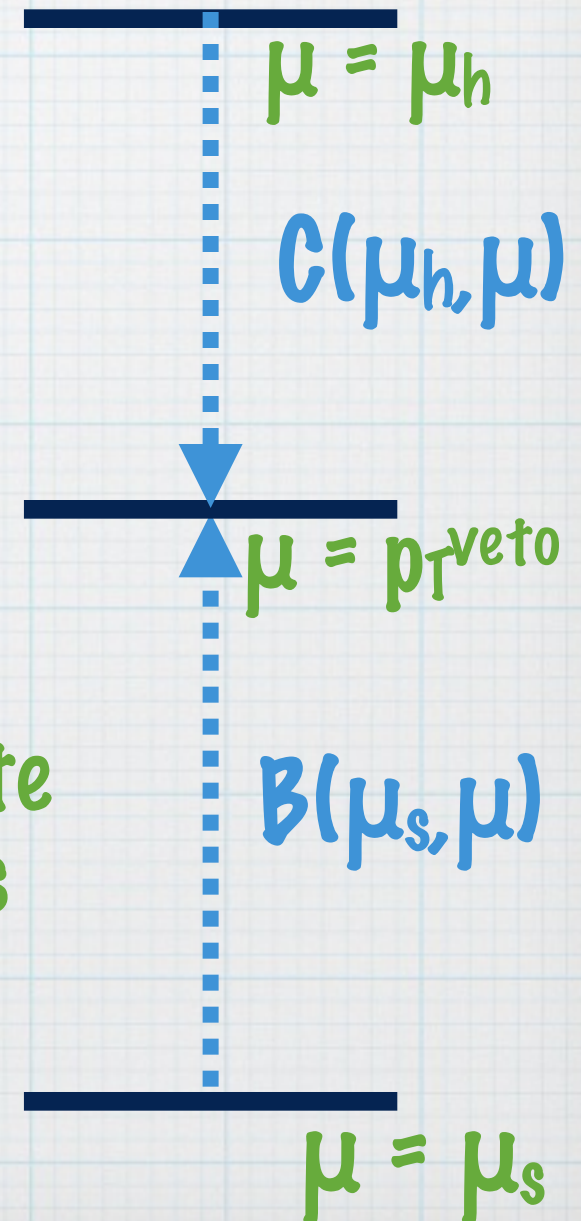
$$\frac{\alpha_s}{4\pi} \log\left(\frac{\mu^2}{\mu_s^2}\right)$$

evolve from μ_s
to p_T^{veto}
(modified DGLAP)

collinear
anomaly

$$\frac{\alpha_s}{4\pi} \log\left(\frac{p_T^{\text{veto}}}{\mu}\right)$$

no large logs
present but
important finite
contributions



Part - III

Complex Scales, Large Logs and Scale Uncertainties

Origin of Complex Scales

$p p \rightarrow V V'$, where $V \in \{W, Z\}$

Analogous to jet-veto cross sections, **Inclusive cross sections** :

$$\sigma = C(\mu) \otimes f_1(\mu) \otimes f_2(\mu) \otimes S(\mu)$$

Wilson Coefficient

PDFs

Soft Function

Logarithms in Wilson coefficient, $C(\mu)$:

$$\log [(-M^2 - i0^+)/\mu^2]$$

- * **Matching of SCET to QCD at $\mu = \mu_h$**
- * **Choice of μ_h ? $\mu_h = M$ minimizes logs....**
- * **....except that branch cut $\Rightarrow -i\pi$ factors so that double logs produce π^2 factors.**
- * **Motivates choice of μ_h in the complex μ^2 -plane, e.g. $\mu_h^2 \approx -M^2$**

Large logs from Complex Scales

Logarithms in Wilson coefficient, $C(\mu)$:

$$\log \left[(-M^2 - i0^+) / \mu^2 \right]$$

- * Matching scale μ_h^2 complex-valued.
- * But PDFs evaluated at factorization scales which are real : $\mu_f^2 \approx M^2$
- * Hierarchy of scales in the complex μ^2 -plane

⇒ Large Logs $\log(\mu_h^2/\mu_f^2)$

- * Phase of μ_h^2 : Θ

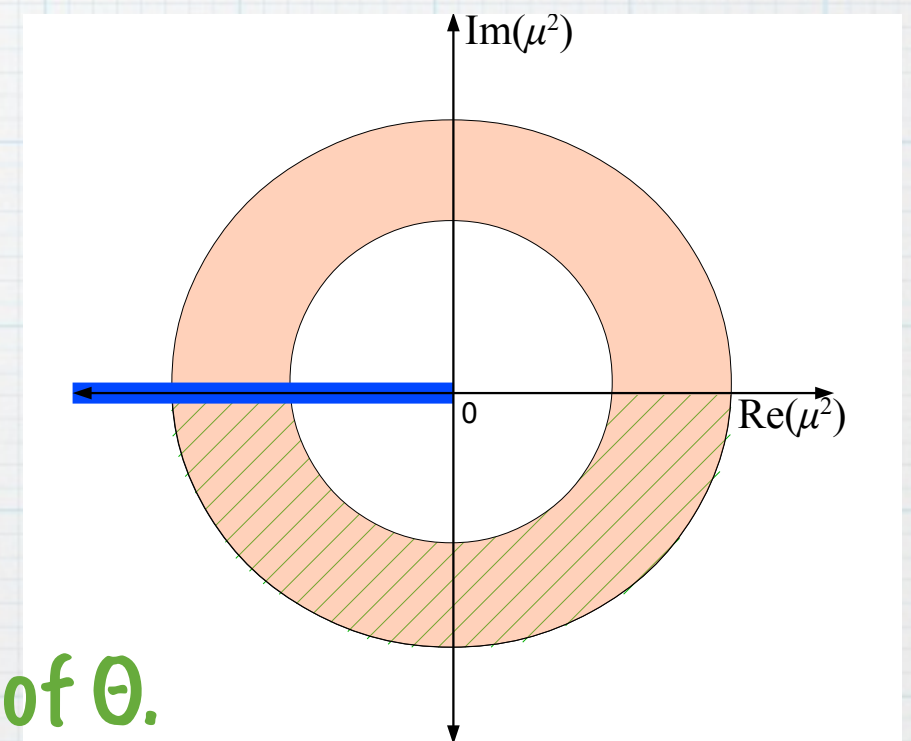
$$\log(\mu_h^2/\mu_f^2) = i \Theta$$

If Logs dominant : $\Theta = -\pi$

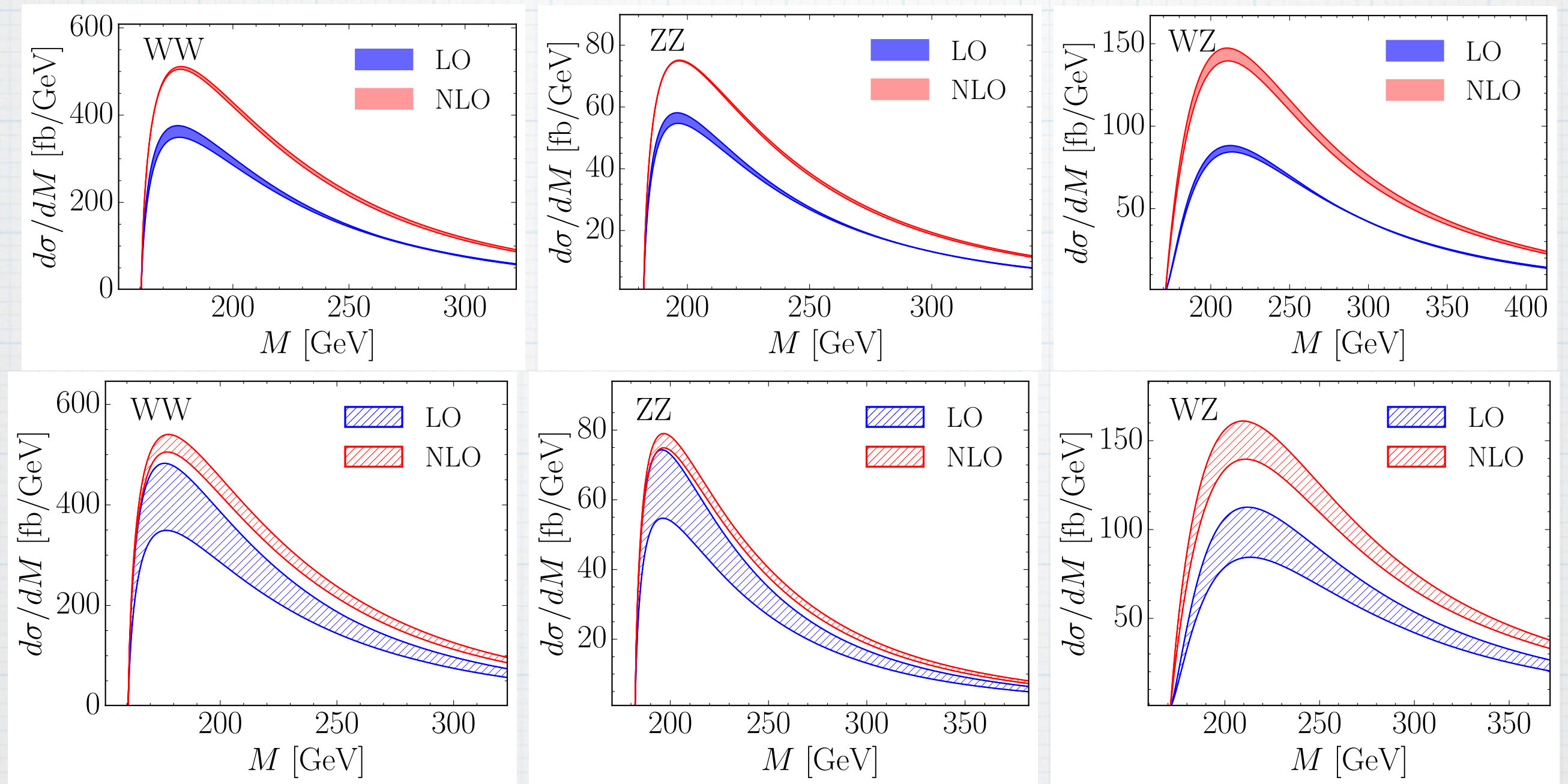
If non-Log terms dominant, no preferred value of Θ .

- * RG equation for $C(\mu)$ known ⇒ Evolve from $\mu_h^2 \rightarrow \mu_f^2 \Rightarrow$ Resum Θ terms.

- * Vary : $-\pi < \Theta < 0$ similar to $M/2 < |\mu_h| < 2M$



Scale Uncertainty



- * 3-4 % increase in central value prediction w.r.t NLO (dynamic scale).
- * Fixed scale (set to average diboson mass) NLO in reasonable agreement.

Part - IV

Results for $WW+0$ jet
production at the LHC

How to count

- * Power Counting parameter in SCET : $\lambda = p_T^{\text{veto}}/M$
- * All calculations at LO in SCET power counting.
- * SCET resums pieces singular in the $\lambda \rightarrow 0$ limit (i.e. $\log^n \lambda$)
- * Corrections beyond the singular pieces : **Power Corrections**
 - ➡ Add them at the end if the full NLO result is known.
 - ➡ (Power Corrections) = NLO - (Singular pieces of NLO)

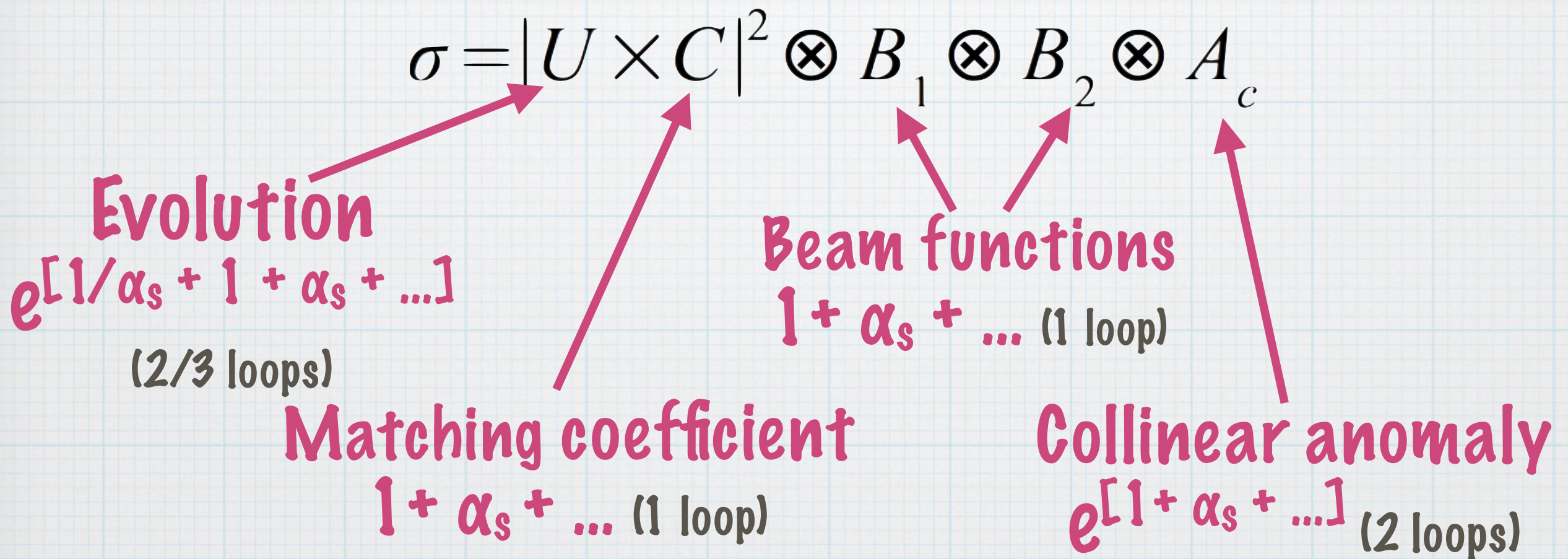
$$\sigma_{\text{tot}} = \sigma_{\text{resum}} + \underbrace{\left(\sigma_{N^n \text{ LO}} - \sigma_{\text{resum}}^{[N^n \text{ LO expansion}]} \right)}_{\text{Power Corrections}}$$

How to count

* α_s Counting in Resummed Perturbation Theory

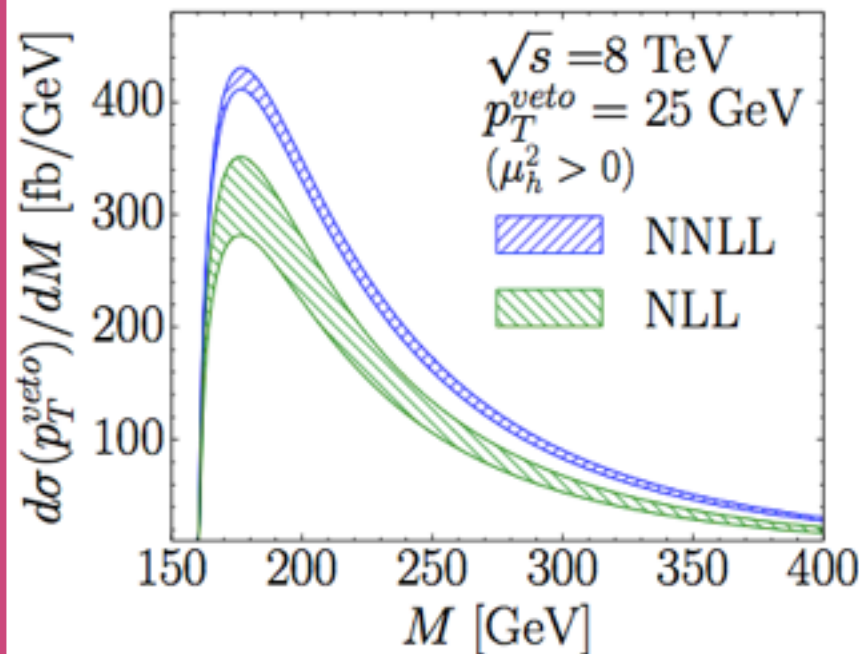
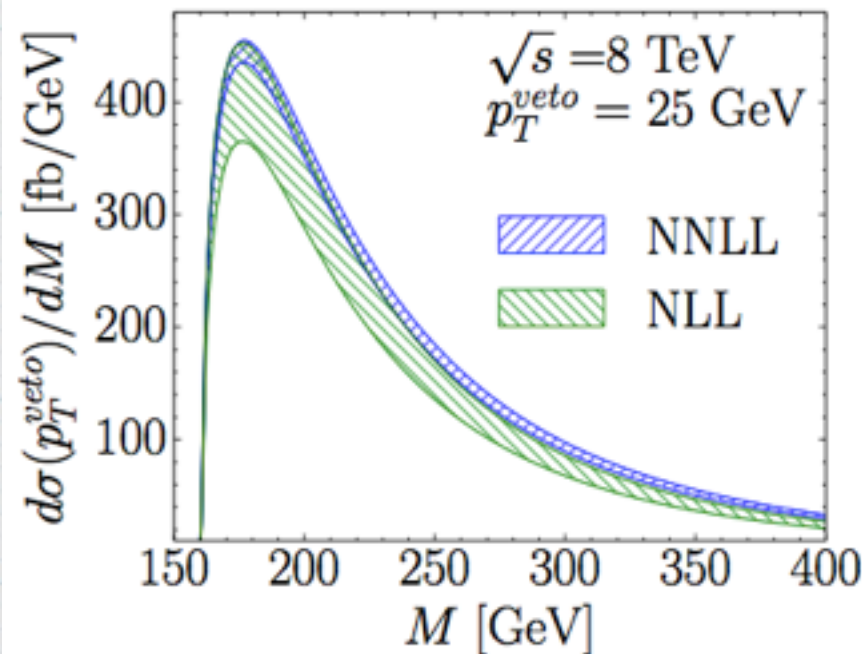
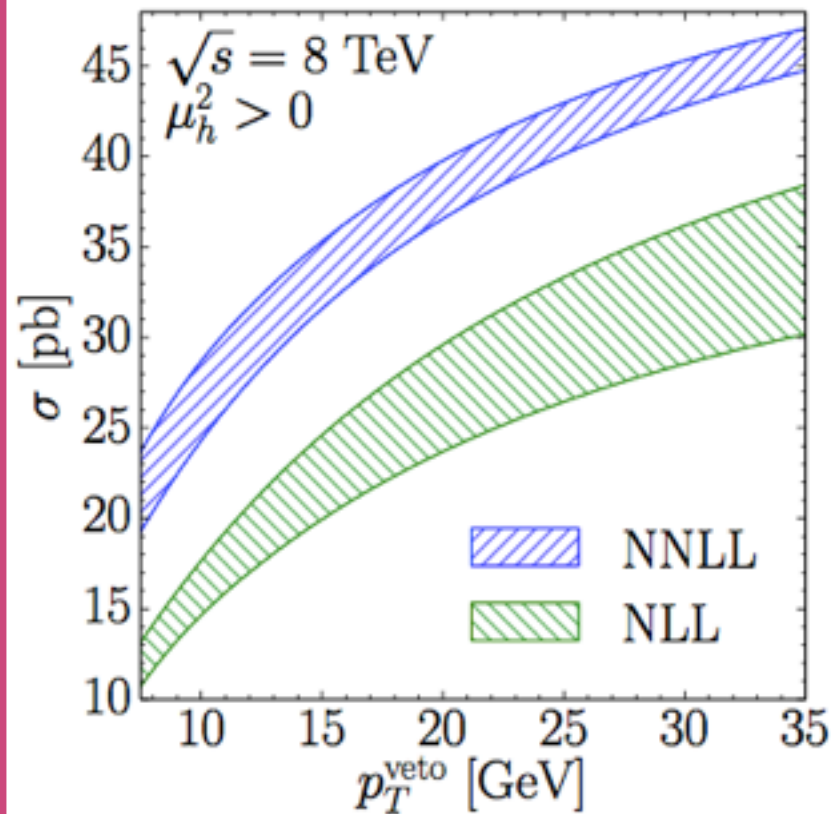
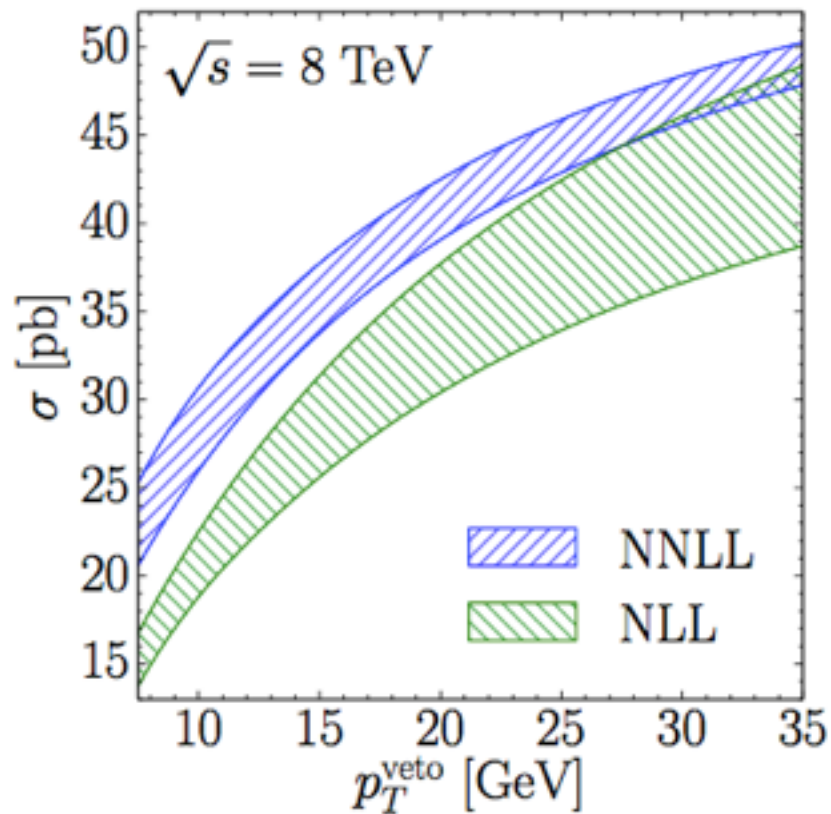
* Count $\log[(p_T^{\text{veto}})^2/M^2]$ as $1/\alpha_s$

* NLL : Keep terms up to $\mathcal{O}(1)$
NNLL : Keep terms up to $\mathcal{O}(\alpha_s)$



All ingredients already known in the literature.

NLL and NNLL Results for $q\bar{q} \rightarrow WW + 0 \text{ jet}$



- * $\mu_f \approx p_T^{\text{veto}}$
- * Scale uncertainty : Vary μ_f and μ_h by factors of 1/2 and 2.
- * anti- k_T jets ($R=0.4$)

π^2 Resummation :

$\log[-M^2/\mu_h^2]$ give factors of π^2 when squared if $\mu_h^2 > 0$.

Better choice : $\mu_h^2 \approx -M^2$

$$\mu_h^2 \approx -M^2$$

$$\mu_h^2 \approx M^2$$

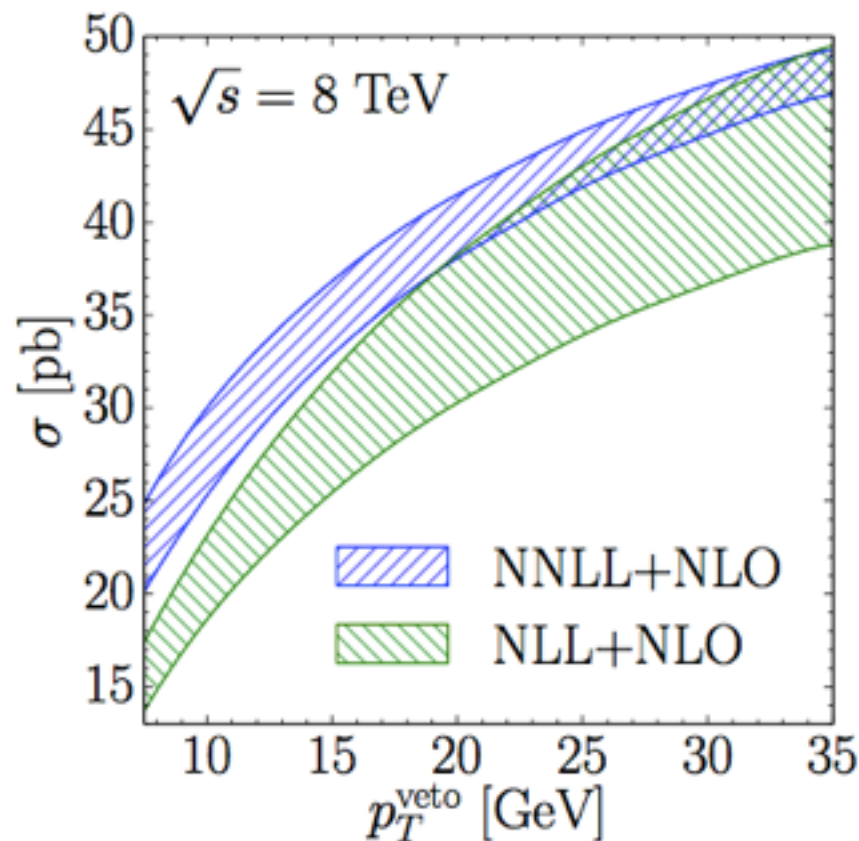
Consistency Checks and Power Corrections

- * Recall : SCET resums terms singular in $p_T^{\text{veto}}/M \rightarrow 0$
 - * Power corrections suppressed by powers of p_T^{veto}/M .
 - * Consistency Check : For small p_T^{veto} , NNLL cross-section expanded to $\mathcal{O}(\alpha_s)$ should match fixed-order NLO calculations.
- ✓ Good agreement between our resummed results expanded to $\mathcal{O}(\alpha_s)$ and MCFM for $q\bar{q} \rightarrow WW$ at NLO in the 0-jet bin for small p_T^{veto} .

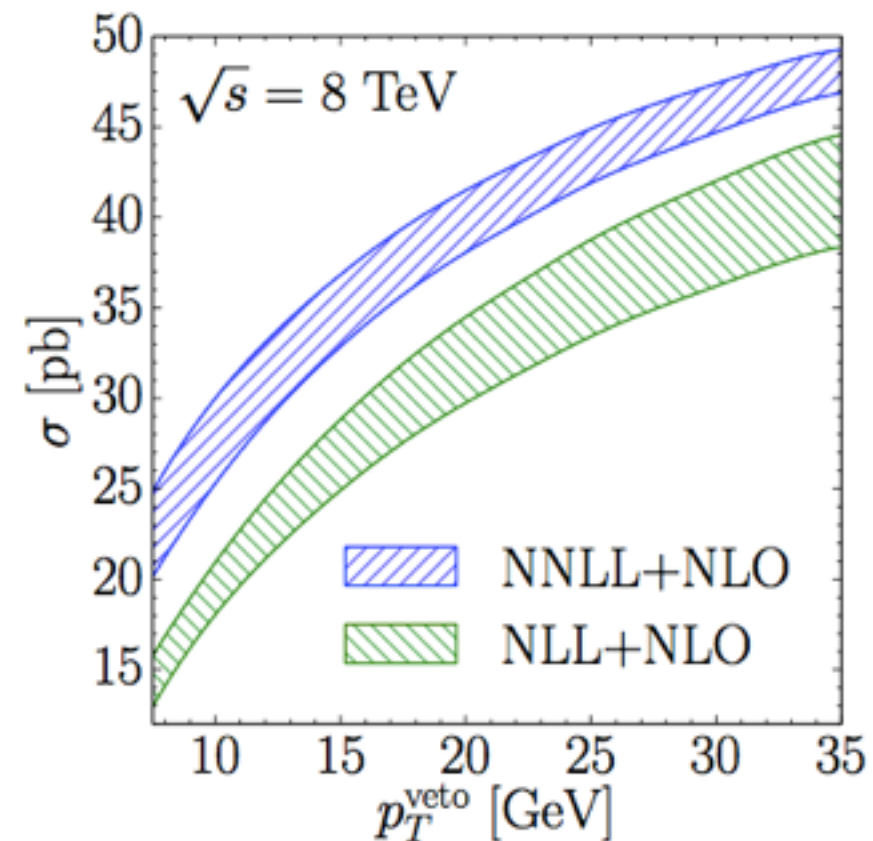
Power Corrections $\lesssim -2\%$

NNLL+NLO Results

‘Consistent’ scheme



‘Inconsistent’ scheme

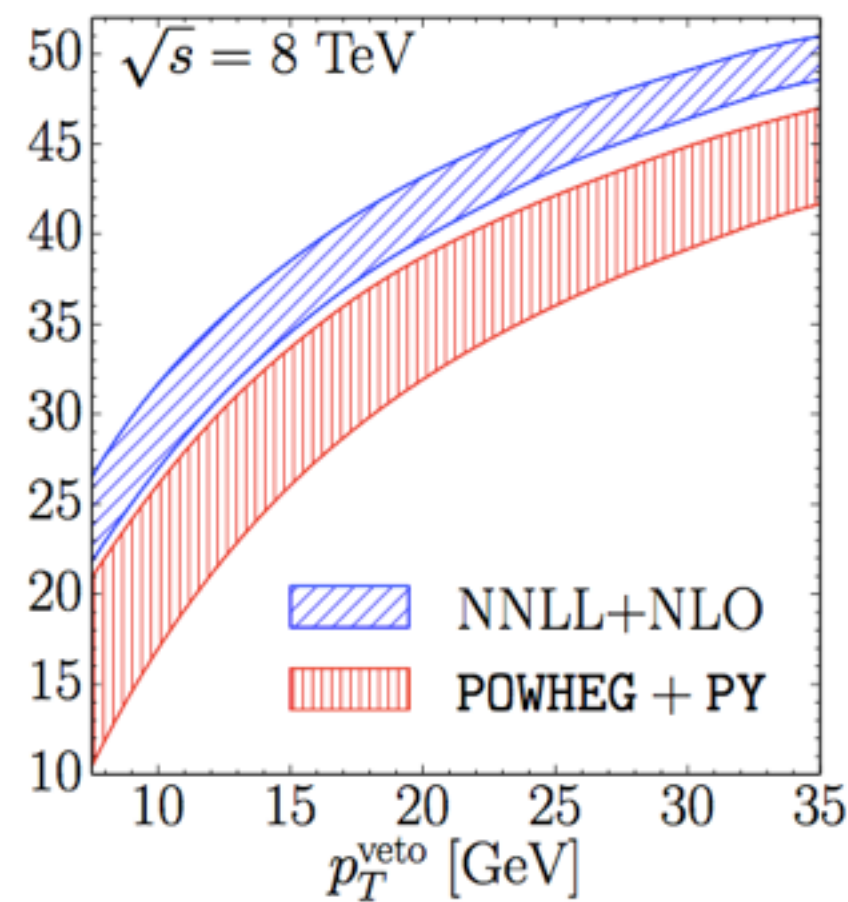
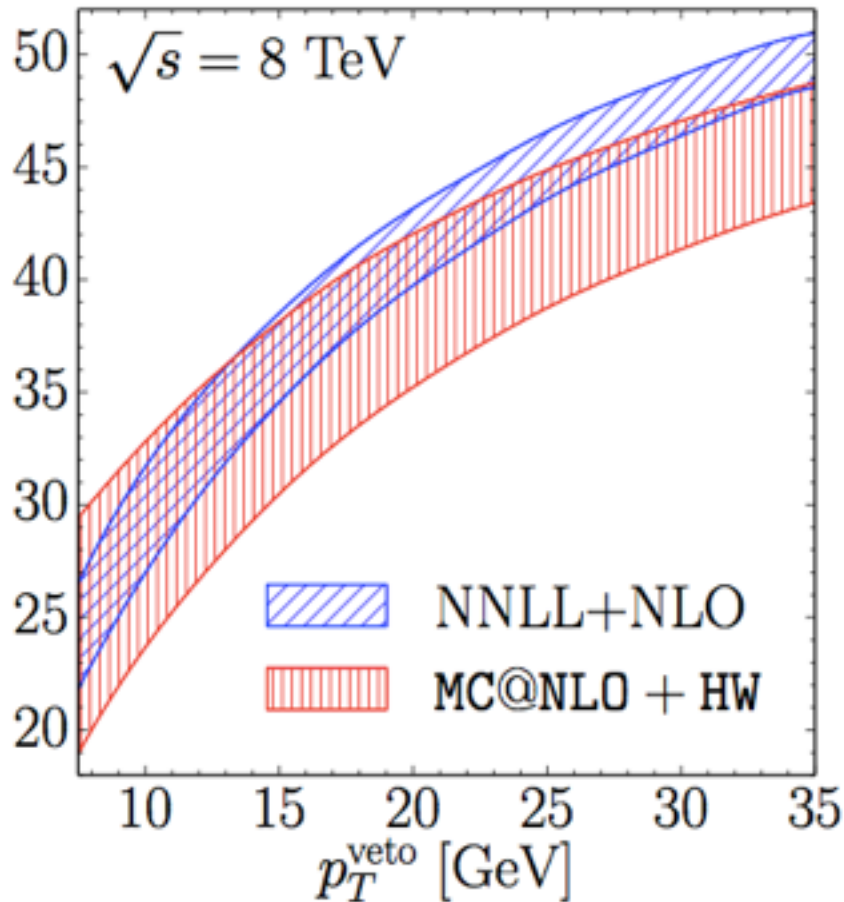
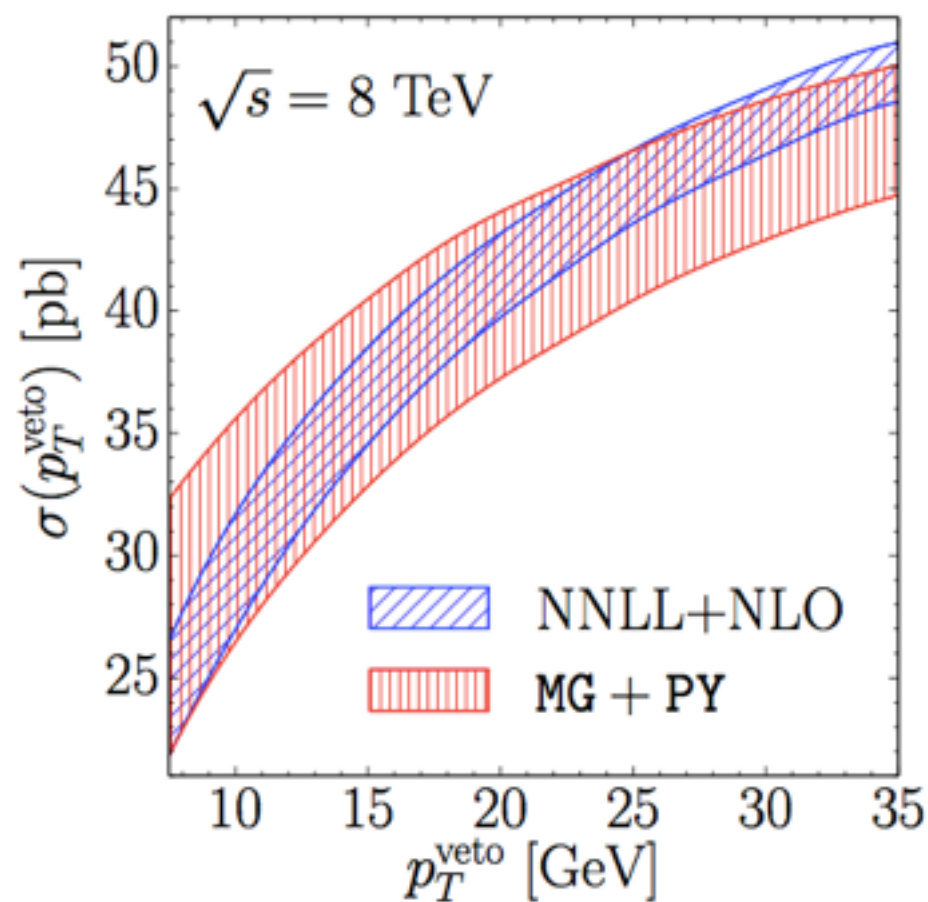


- * ‘Inconsistent scheme’ : Improved version of NLL by including $\mathcal{O}(\alpha_s)$ terms in the matching coefficient.
- * Difference between NLL and NNLL is dominated by two-loop effects of jet-veto

$$\left(p_T^{\text{veto}} / M \right) \alpha_s^2 [1 + \log R + R^2 + R^4 + \dots]$$

Comparison with MC+Parton Showers

(Includes LO gg contribution assuming 100% of them pass jet-veto)



WW+0/1/2 jet matched :
LO Madgraph5 + Pythia6

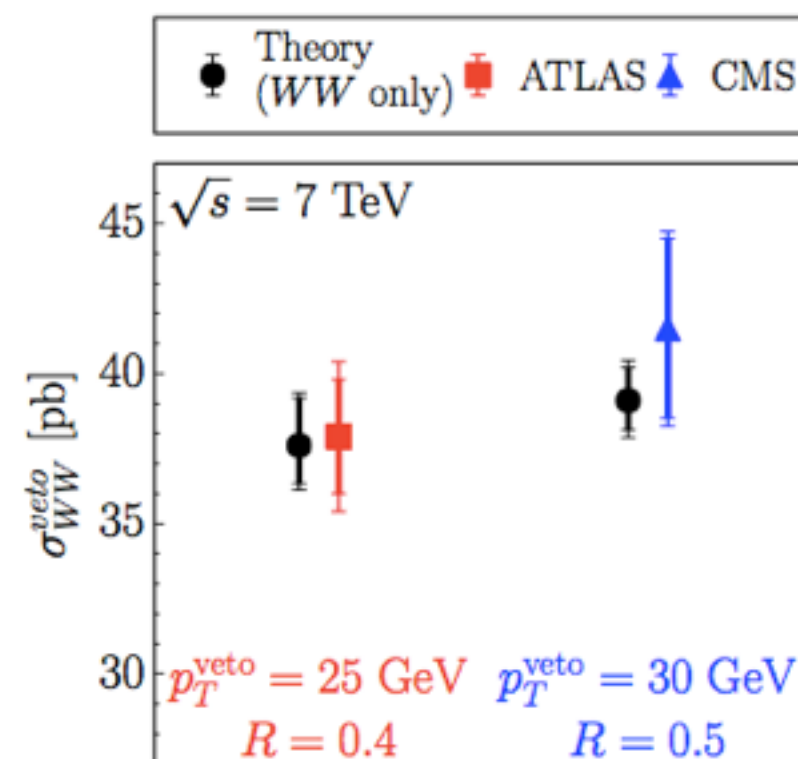
MC@NLO +
Herwig6

Powheg v1 +
Pythia6

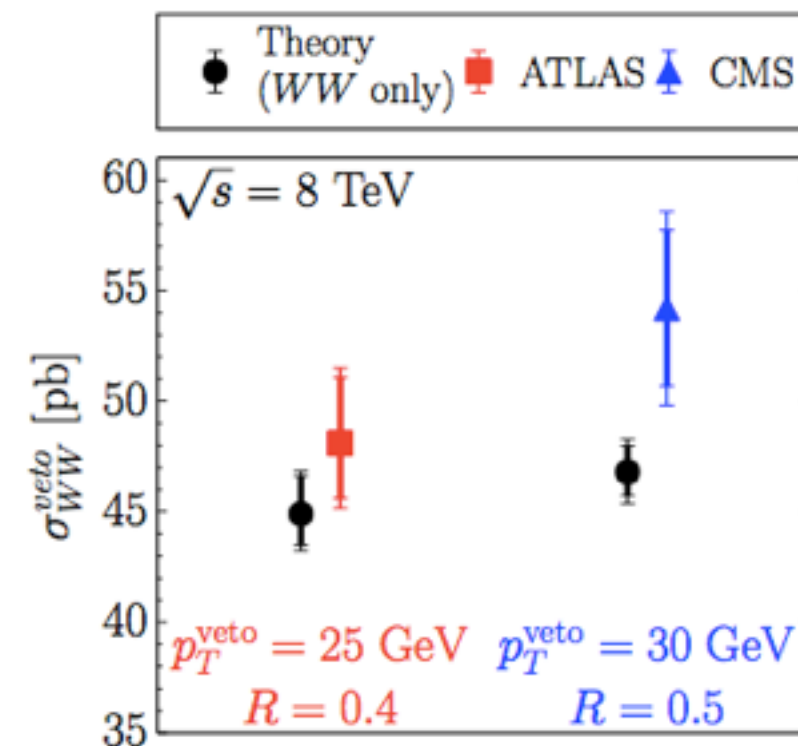
Jet algorithm : anti- k_T , $R=0.4$
CTEQ6L for LO MC, CT10nlo for NLO MC,
MSTW08nnlo for NNLL+NLO

Comparison with LHC data

	$\sqrt{s} = 7 \text{ TeV}$	
	$R = 0.4$ $p_T^{\text{veto}} = 25 \text{ GeV}$	$R = 0.5$ $p_T^{\text{veto}} = 30 \text{ GeV}$
ATLAS $\sigma_{WW}^{\text{veto}}$ [pb]	$37.9^{+3.8\%+5.0\%+3.8\%}_{-3.8\%-5.0\%-3.8\%}$	—
CMS $\sigma_{WW}^{\text{veto}}$ [pb]	—	$41.5^{+3.8\%+7.2\%+2.3\%}_{-3.8\%-7.2\%-2.3\%}$
Theory $\sigma_{WW}^{\text{veto}}$ [pb]	$37.6^{+4.2\%}_{-3.4\%}$	$39.1^{+2.8\%}_{-2.5\%}$
Theory $\sigma_{h \rightarrow WW}^{\text{veto}}$ [pb]	$2.1^{+13.5\%}_{-11.4\%}$	$2.3^{+11.5\%}_{-10.6\%}$

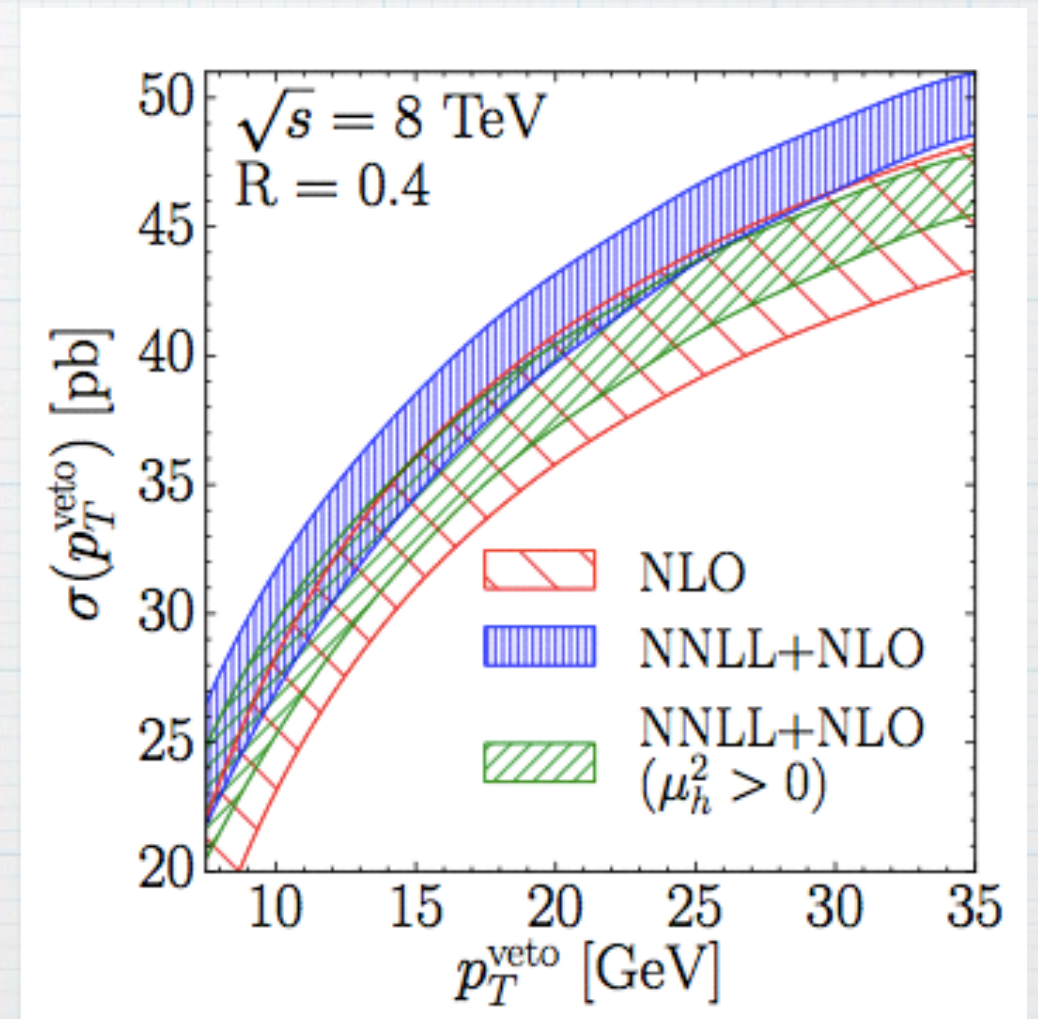
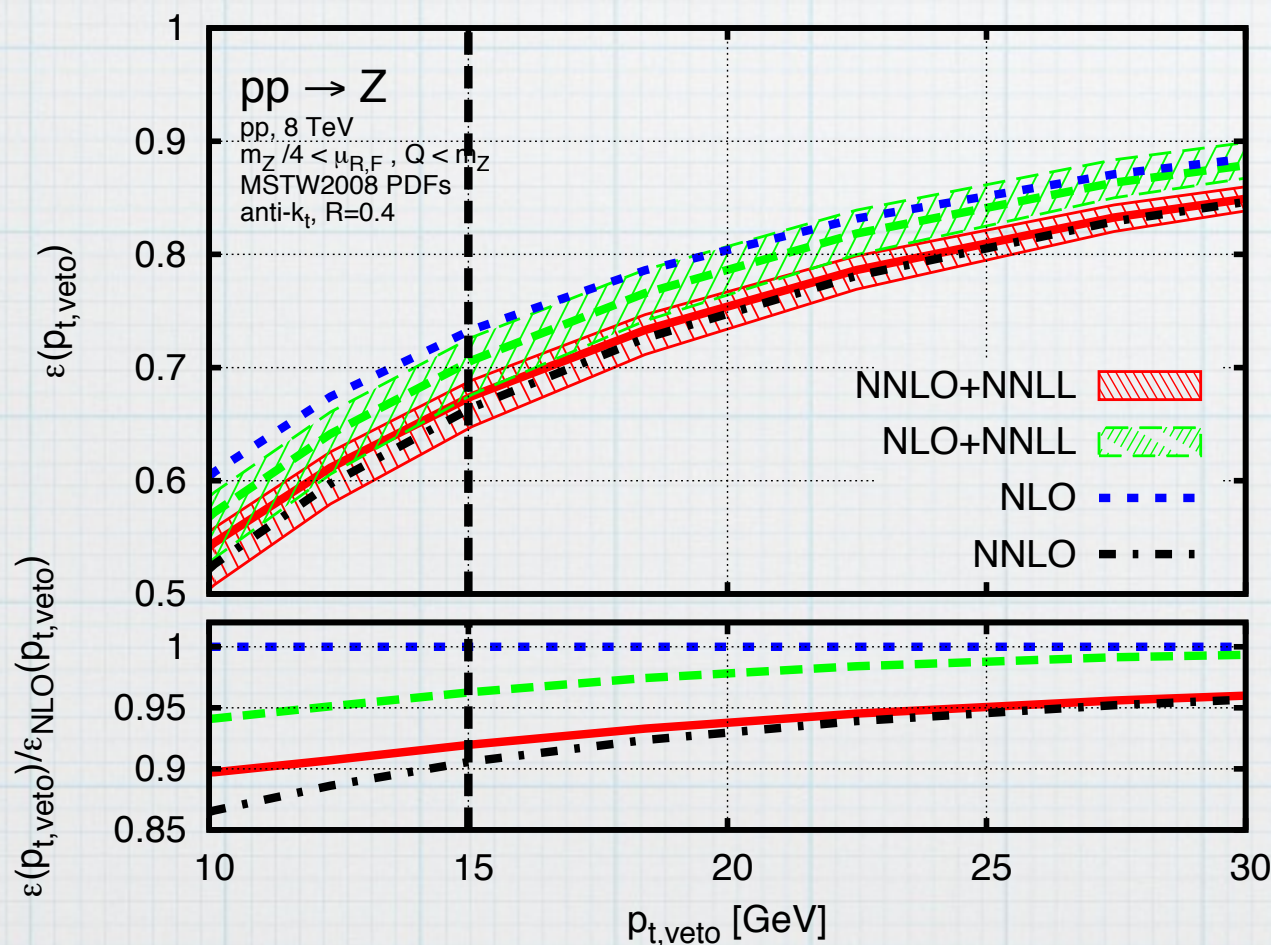


	$\sqrt{s} = 8 \text{ TeV}$	
	$R = 0.4$ $p_T^{\text{veto}} = 25 \text{ GeV}$	$R = 0.5$ $p_T^{\text{veto}} = 30 \text{ GeV}$
ATLAS $\sigma_{WW}^{\text{veto}}$ [pb]	$48.1^{+1.7\%+6.2\%+3.1\%}_{-1.7\%-5.2\%-2.9\%}$	—
CMS $\sigma_{WW}^{\text{veto}}$ [pb]	—	$54.2^{+4.0\%+6.5\%+4.4\%}_{-4.0\%-6.5\%-4.4\%}$
Theory $\sigma_{WW}^{\text{veto}}$ [pb]	$44.9^{+3.8\%}_{-3.1\%}$	$46.8^{+2.5\%}_{-2.3\%}$
Theory $\sigma_{h \rightarrow WW}^{\text{veto}}$ [pb]	$2.6^{+13.3\%}_{-11.7\%}$	$2.9^{+11.5\%}_{-11.5\%}$



Similar Calculations

- * [\[arXiv:1407.4481\]](#) Transverse momentum resummation
Patrick Meade, Harikrishnan Ramani, Mao Zeng
- * 3-7% reduction in discrepancy
- * [\[arXiv:1410.4745\]](#) NNLL+NNLO extrapolation from Drell-Yan
Pier Francesco Monni, Giulia Zanderighi



Todo for experimentalists

- * Jet-veto cross sections at high invariant mass Drell-Yan.
- * Cross-sections as a function of p_T^{veto} and R (jet radius parameter) for diboson and Drell-Yan (at high invariant mass).